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The Dynamic Range of Ultra-High Resolution Cryogenic Gamma-ray Spectrometers

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Abstract

We are developing high-resolution cryogenic gamma-ray spectrometers for nuclear science and non-proliferation applications. The gamma-ray detectors are composed of a bulk superconducting Sn foil absorber attached to multilayer Mo/Cu transition-edge sensors (TES). The energy resolution achieved with a 1 x 1 x 0.25 mm^3 Sn absorber is 50 - 90eV for γ-rays up to 100 keV and it decreases for large absorber sizes. We discuss the trade-offs between energy resolution and dynamic range, as well as development of TES arrays for higher count rates and better sensitivity.

Keywords: Micro-calorimeter; Low temperature detector; Gamma-ray spectroscopy

1.Introduction

The high-energy resolution of microcalorimeters is an enabling technology for enhancing the identification of gamma-ray emission lines from different isotopes for precise determination of the level of enrichment in nuclear materials. We have achieved very high-energy resolution, e.g., 50-90 eV [1] up to 100 keV energy range with a 1 x 1 x 0.25 mm3 Sn absorber γ-ray spectrometer. However, the dynamic range of this detector is limited. The absorber sizes must be increased to probe high-energy γ-ray emissions which are important for nuclear and non-proliferation monitoring applications.

We investigate the effects of increasing the gamma-ray absorber sizes and discuss the trade-offs between energy resolution and dynamic range of these detectors.

1.1 Mo/Cu multilayer TES with bulk Sn absorbers

The multilayer Mo/Cu transition-edge sensor (TES) consists of 15 alternating layers of 4 Å thick Mo and 9 Å thick Cu films sputter-deposited on a 500 nm SiN membrane on a 4" Si wafer and is capped by an additional layer of Cu [2]. A polycrystalline bulk Sn foil absorber is attached to the top of the TES by 2850 Stycast. The epoxy forms the strong thermal link between the TES and the absorber and the SiN membrane forms the weak link between the detector system and the cold bath.

To further increase the count rate of our -ray spectrometers, we are currently developing multi-pixel arrays with frequency domain multiplexed readout in collaboration with UC Berkeley [3].

1.2 Scaling of energy-resolution with absorber size

We present the data from three γ-ray detectors with 500 x 500 m^2 multilayer TES and three different size bulk Sn absorbers. The volumes of the three absorbers are 1 x 1 x 0.25 mm^3 (small), 1.2 x 1.2 x 0.25 mm^3 (medium), and 2 x 2 x 0.25 mm^3 (large) respectively.

The energy resolutions of these three detectors are shown in Fig 1. As expected the larger absorber detector has a much worse energy resolution at the 30 to 140 keV range. Surprisingly, the two detectors with larger absorbers show a decrease in line width at 136.47 keV. This may reflect the variations in sensitivity along the superconducting transition.

1.3 Dynamic range variation with absorber size

The heat capacity of the microcalorimeter is dominated by the heat capacity of the Sn foil absorber C_{abs}. At 100 mK operating temperature the heat capacity of the TES (C_{TES}) is ~1 pJ/K, and C_{abs} ~10 pJ/K. Also the thermal conductance of the epoxy between the absorber and TES is G_{abs} ~10 nW/K, and the thermal conductance to the cold bath through the SiN membrane is G_{SiN} ~1 nW/K [4]. The dynamic range and the efficiency of the detector also increase with absorber volume. The top graph in Fig. 2 shows the dynamic range of the three -ray detectors. The detector with the smallest absorber volume is driven off its superconducting transition for γ-ray energy above 150 keV. We need to use detectors with larger -ray absorbers as the γ-ray energy increases. The bottom graph in Fig. 2 shows the composite -spectrum from calibration sources ^{241}Am, ^{57}Co and ^{226}Ra using the 1 x 1 x 0.2 mm^3, 1.2 x 1.2 x 0.25 mm^3 and the 2 x 2 x 0.25 mm^3 sized -ray detectors respectively. The best energy resolution of 52 eV is achieved with smallest absorber size at 59.5 keV -line from the ^{241}Am source. The medium sized absorber with 93 eV energy resolution can successfully resolve the two Sn Kα escape lines $K\alpha_1$ and $K\alpha_2$ arising from ^{57}Co 122.06 keV γ-emission at 96.78 keV and 97.01 keV. Large absorber volume detectors with high efficiency and higher dynamic range and consequently reduced energy resolution are appropriate for high-energy operation (^{226}Ra γ-line >200 keV) where the lines are also further apart.

2. Discussion

We characterized three multilayer Mo/Cu TES γ-ray detectors with different sized absorbers and have examined the trade-offs between energy resolution, detection efficiency and dynamic range. For many non-proliferation applications increased efficiency is more desirable than the highest energy resolution. For example, the ^{234}Th/Th K_2 lines at 92 keV and the ^{235}U/^{226}Ra lines at 186 keV are very important for measuring U enrichment and monitoring uranium mining activities. A γ-ray detector with 200-eV resolution will be sufficient to resolve these lines and increased absorption efficiency will be very useful to examine dilute samples.

We are developing cryogenic γ-ray spectrometers with energy resolution of ~50-90 eV FWHM below 100 keV. Higher energy operation is possible by increasing the γ-ray absorber size with higher absorption efficiency but with lower energy resolution. Cryogenic γ-ray spectrometers can improve the accuracy of non-destructive nuclear isotopic ratio measurements. Precise measurements of U enrichments and Pu isotopes provide vital information about the origin, history, and possible purpose of the sample that are useful for nuclear attribution and non-proliferation applications. We are currently developing a multi-pixel -ray spectrometer with multiplexed readout to increase sensitivity, count-rate, and efficiency.

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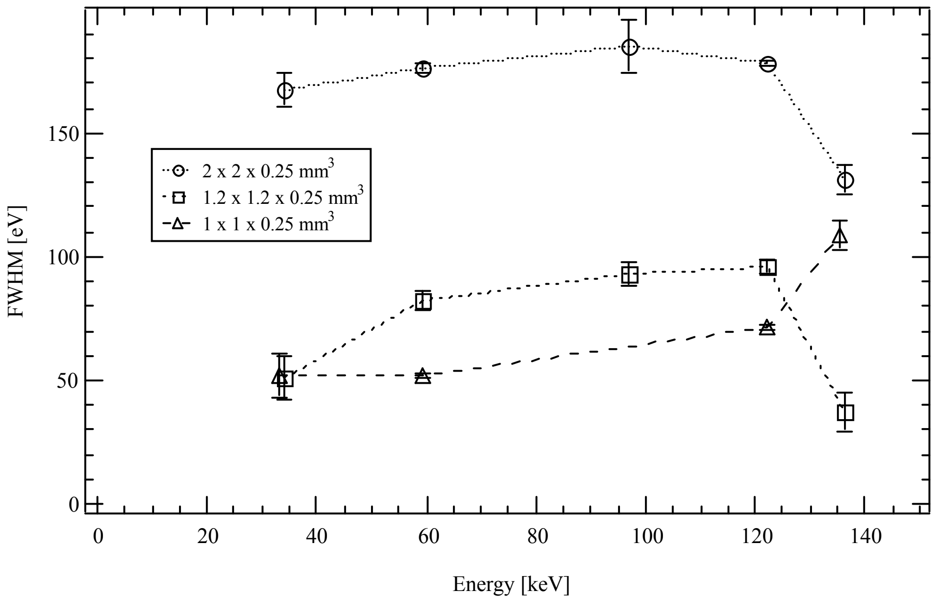

Fig. 1. Scaling of the energy resolution of -ray detectors with Sn absorber sizes up to140 keV region. Energy resolution degrades with increasing absorber volume at the same operating temperature of 100 mK.

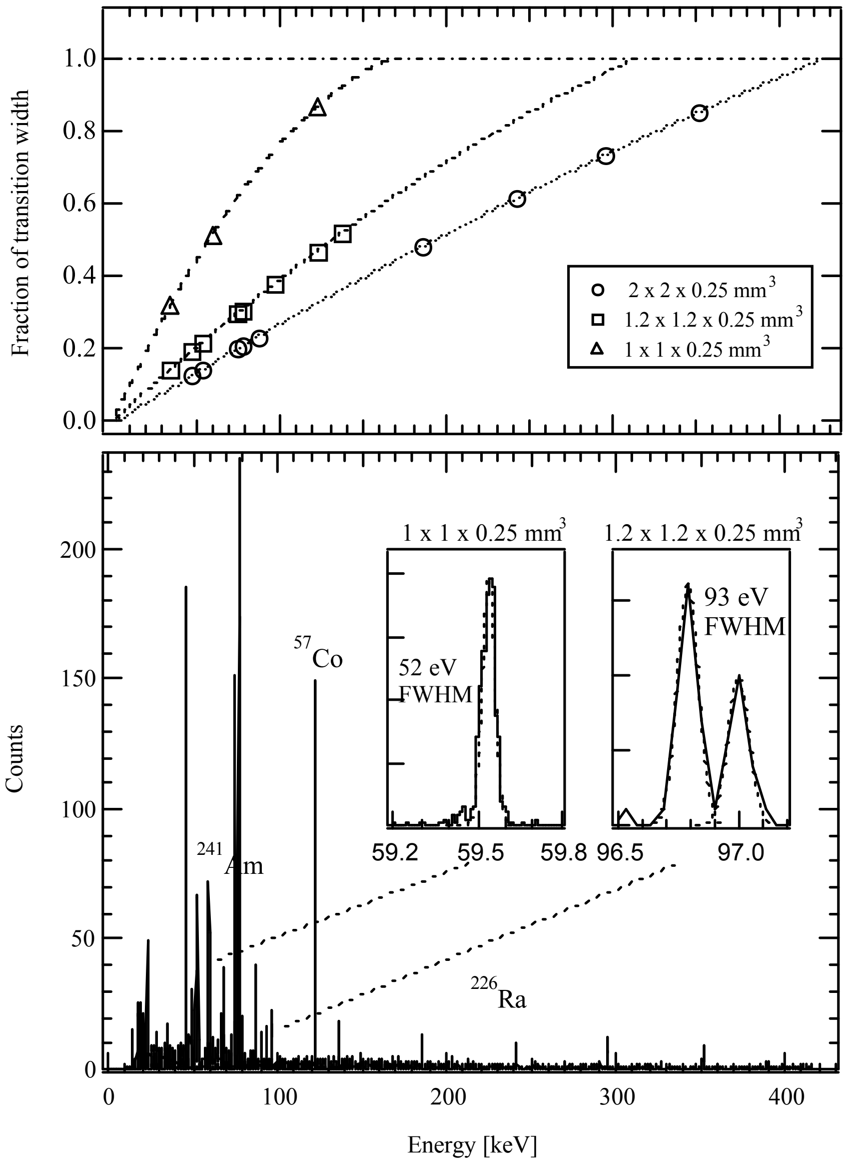

Fig. 2. (Top) The dynamic ranges of the three γ-ray detectors versus energy. The 1x1x0.25 mm^3 absorber drives the TES off its 1 mK wide transition in the 150 keV energy range. As the absorber size is increased so does the dynamic range of the detector. (Bottom) Calibration spectra from ^{241}Am, ^{57}Co and ^{226}Ra sources. The energy resolution of the 1 x 1 x 0.25 mm^3 Sn absorber detector at 59.5 keV energy and the energy resolution of the 1.2 x 1.2 x 0.25 mm^3 Sn absorber detector at 96-97 keV energy are shown in insets.